

The Spatial Distribution of [O I] in Comet
Hale-Bopp from 2,000 to 1×10^6 km:
Evidence for Spatial Asymmetry

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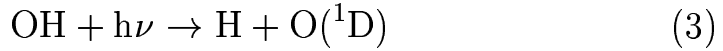
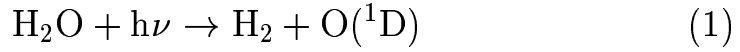
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Abstract

The exceptional brightness and long observational window of Comet Hale-Bopp provided a remarkable opportunity to study both the cometary neutral coma and the cometary plasma in the coma and ion tail. In response to this opportunity, a coordinated earth-based observing campaign for Comet Hale-Bopp was undertaken involving personnel from the University of Wisconsin and Goddard Space Flight Center. Seven different instruments were used to measure cometary emissions for H- α , OH, O, H₂O⁺, NH₂, C, CN, C₂, and the continuum. Here we present observations and model analysis for the O(¹D) ([O I] 6300 Å) emission line in Comet Hale-Bopp. In March 1997, four instruments on Kitt Peak observed the comet in O(¹D). Two of the instruments were multi-object spectrographs (MOS) fed by the Wisconsin, Indiana, Yale, NRAO (WIYN) telescope. The third instrument was the 6 inch Fabry-Perot spectrometer that comprises the Wisconsin H α Mapper (WHAM), which recorded narrow band images over a 1° field of view. The fourth instrument was a 2 inch Fabry-Perot spectrometer on the McMath-Pierce main telescope which recorded high resolution ($\lambda/\Delta\lambda = 80,000$) spectra of the [O I] 6300 Å line of the central 6 arcminutes of the comet. The combination of MOS and Fabry-Perot data covers spatial scales ranging from 2,000 km to 1×10^6 km. Modeling analysis for the O(¹D) observations using the state-of-the-art Monte Carlo Particle Trajectory Model (MCPTM) of Combi & Smyth (1988) including recent refinements (Combi, Pos, & Smyth 1993) yield preliminary values of the water production rate of $\sim 1 \times 10^{31}$ molecules/sec. Evidence of an unexpected asymmetry in the O(¹D) distribution has been detected in WHAM Fabry-Perot and the hydra MOS datasets.

Introduction

Water is the most abundant volatile species in the comae of comets. Water is photo-dissociated by sunlight according to these reactions:



where $\text{O}(^1\text{D})$ refers to an excited state of oxygen which decays to the ground state in one of two forbidden transitions with a lifetime of ~ 100 s (Figure 1).

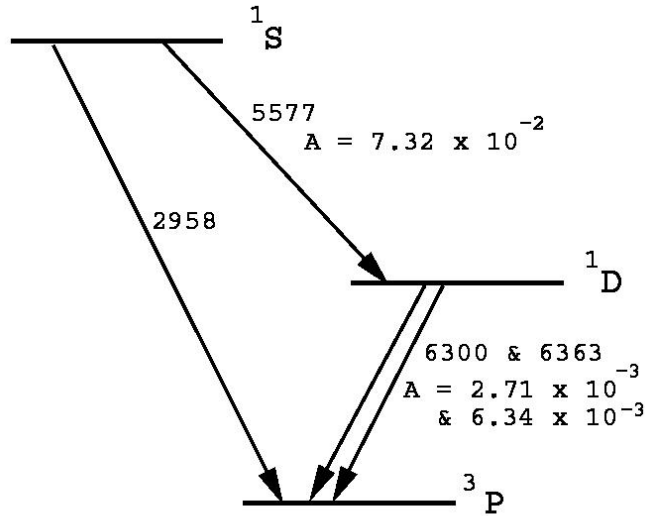


Figure 1: Portion of atomic oxygen energy level diagram.

The decay of $\text{O}(^1\text{D})$ is easily detected with spectroscopic techniques or narrow-band imaging. Given an assumed water production rate, the distance to the sun (amount of sunlight), the appropriate cross-sections, and a model of how water molecules

move away from the comet, it is possible to calculate the expected distribution of $O(^1D)$. Since solar radiation tends to dissociate water molecules rather than impart momentum and the solar wind has a small cross-section of interaction with water, the distribution of water, and hence $O(^1D)$, is expected (and generally observed) to be spherically symmetric (e.g. Magee-Sauer *et al.* 1988, Schultz *et al.* 1993). It is interesting to note that two of the datasets presented in this work observed and reduced with independent techniques show asymmetry between the sunward and tailward directions (Figures 5 and 7)

In this work, we use the Monte Carlo Particle Trajectory Model (MCPTM) of Combi & Smyth (1988) including recent refinements (Combi, Pos, & Smyth 1993) to describe the distribution of water and its photo-dissociation products for projected distances between 10,000 and 1×10^6 km from the comet nucleus. Preliminary water production rates based on fits to the data are 1.8×10^{31} molecules/sec for March 5 and 8.7×10^{30} molecules/sec for March 16.

Observations

Observations of comet Hale-Bopp over a wide range of wavelengths were conducted by this team from Aug 16, 1996 through April 29, 1997. This poster presents $O(^1D)$ observations in March 1997 which were recorded by four instruments on Kitt Peak.

Two of the instruments were multi-object spectrographs (MOS) fed by the Wisconsin, Indiana, Yale, NRAO (WIYN) telescope. The MOS spectra were recorded over a 300 Å range centered at 6250 Å with a resolving power of $(\lambda/\Delta\lambda) \sim 15,000$. The hydra MOS recorded spectra from 95 points arrayed in 6 concentric rings centered on the comet nucleus. Each hydra fiber was 3 arcseconds in diameter. The densepack MOS consisted of 97

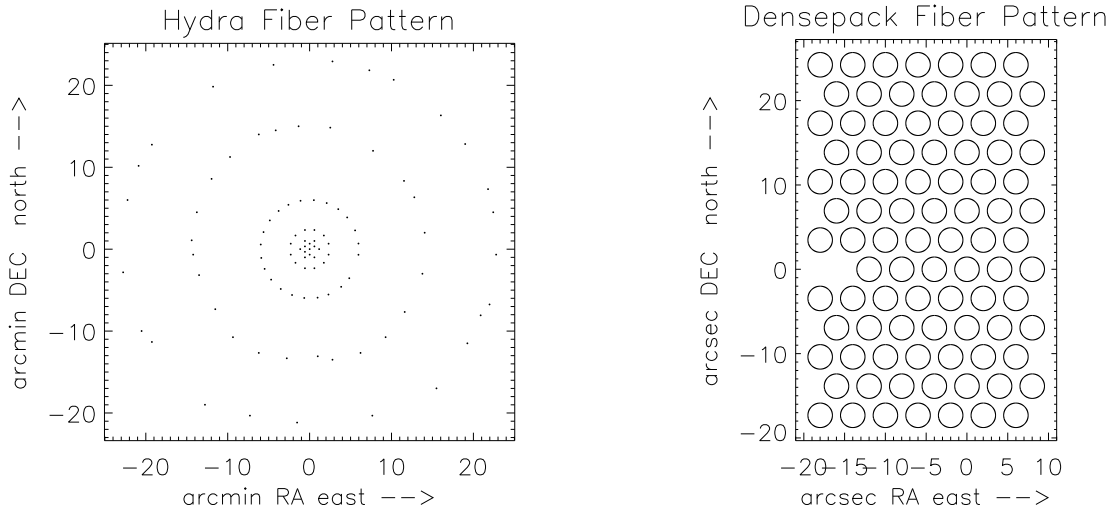


Figure 2: Hydra and Densepack fiber configurations.

3 arcsec fibers in a hexagonal array with the minimum separation between fibers of 4 arcsecs.

The third instrument was the 6 inch Fabry-Perot spectrometer that comprises the Wisconsin H α Mapper (WHAM). WHAM can be used to record spectra over a 200 km/s range (4 Å at 6300 Å) with a resolving power of $(\lambda/\Delta\lambda) \sim 30,000$, or narrow band images over as little as ~ 10 km/s.

The fourth instrument was a 2 inch Fabry-Perot spectrometer on the McMath-Pierce main telescope which recorded high resolution $(\lambda/\Delta\lambda = 80,000)$ spectra of the [O I] 6300 Å line of the central 6 arcminutes of the comet.

The combination of MOS and Fabry-Perot data covers spatial scales ranging from 2,000 km to 1×10^6 km.

Data Analysis

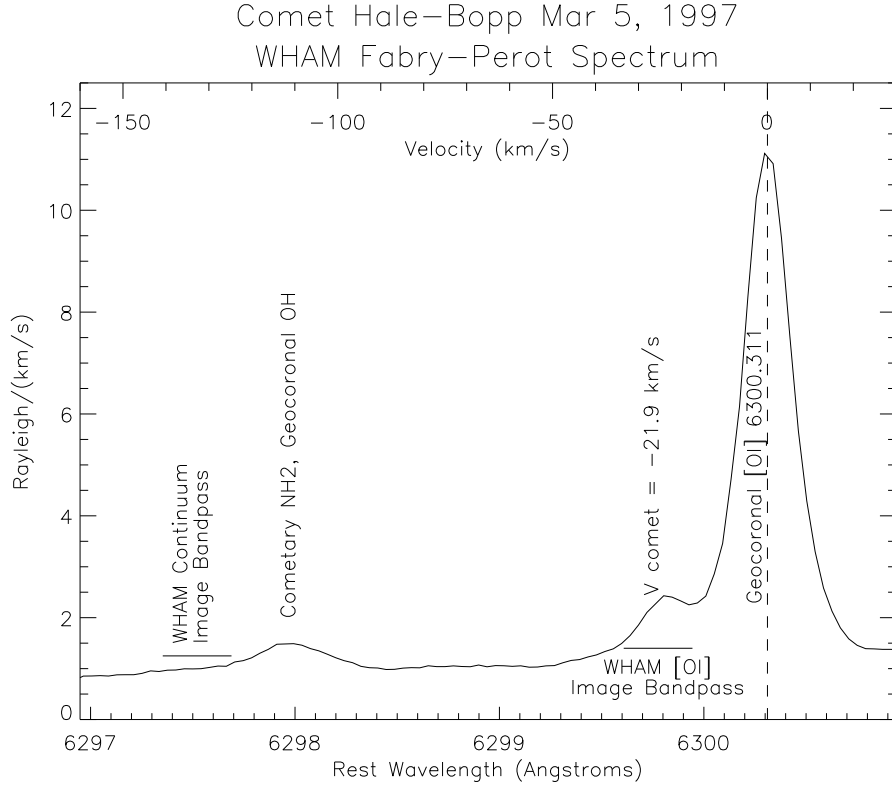


Figure 3: WHAM spectrum of Comet Hale-Bopp (March 5, 1997).

Geocoronal $O(^1D)$ emission is one of the principle complications in the analysis of these data. Figure 3 shows a spectrum taken by the WHAM Fabry-Perot spectrometer over a 1° field of view centered on the head of the comet. The dominant feature is the geocoronal $[O\ I]$ emission. In general, geocoronal emission can be variable with time and over large scales (~ 10 s of degrees). Here, the geocoronal $[O\ I]$ emission has an intensity of ~ 200 Rayleighs.

The bandpass used to record the WHAM $[O\ I]$ images of Hale-Bopp is shown as a short line segment in Figure 3. In order to measure the continuum contribution to the $[O\ I]$ images,

the WHAM instrument bandpass was moved $\sim 2\text{\AA}$ lower. Since WHAM could not fully separate the geocoronal and cometary [O I] emission, images were taken on and off the cometary [O I] line with the WHAM siderostat aimed 3° west of the comet. On March 5, five series of on-comet, on-line; on-comet, off-line; off-comet, on-line; off-comet, off-line images were taken. Each on-comet image was sky-subtracted and then the off-line (continuum) image was subtracted from the on-line comet image.

Distortions in the WHAM Fabry-Perot etalons have complicated the analysis of the image data. The effects of these distortions have been divided out to first order using an image of the night sky [O I] line. However, residual effects remain, as can be seen by the erratic behavior of the [O I] radial profile for projected distances $> 1 \times 10^6$ km from the nucleus (Figure 6).

The velocity dispersion of [O I] is expected to be only a few km/s. A spectrum at high resolution recorded by the 2 inch Fabry-Perot system shown in Figure 4 confirms this to be the case in comet Hale-Bopp.

The spectra taken with the fiber-fed MOSs on the WIYN telescope did not have sufficient resolving power to separate the geocoronal and cometary [O I] features. Since the densepack fibers were arrayed within 30 arcsec of the nucleus, the sky background of < 1000 R is negligible compared to the comet intensity of $> 1 \times 10^5$ R (see Figure 6). On the other hand, comet [O I] flux in forth ring of hydra fibers is only a few times the sky background. Thus, determining the geocoronal [O I] brightness is crucial for the correct interpretation of the hydra data. For each exposure, the flux values in the fifth and hydra sixth rings were identical to within statistical errors, thus, the average value was taken to be the sky background and subtracted from the rest of the fibers.

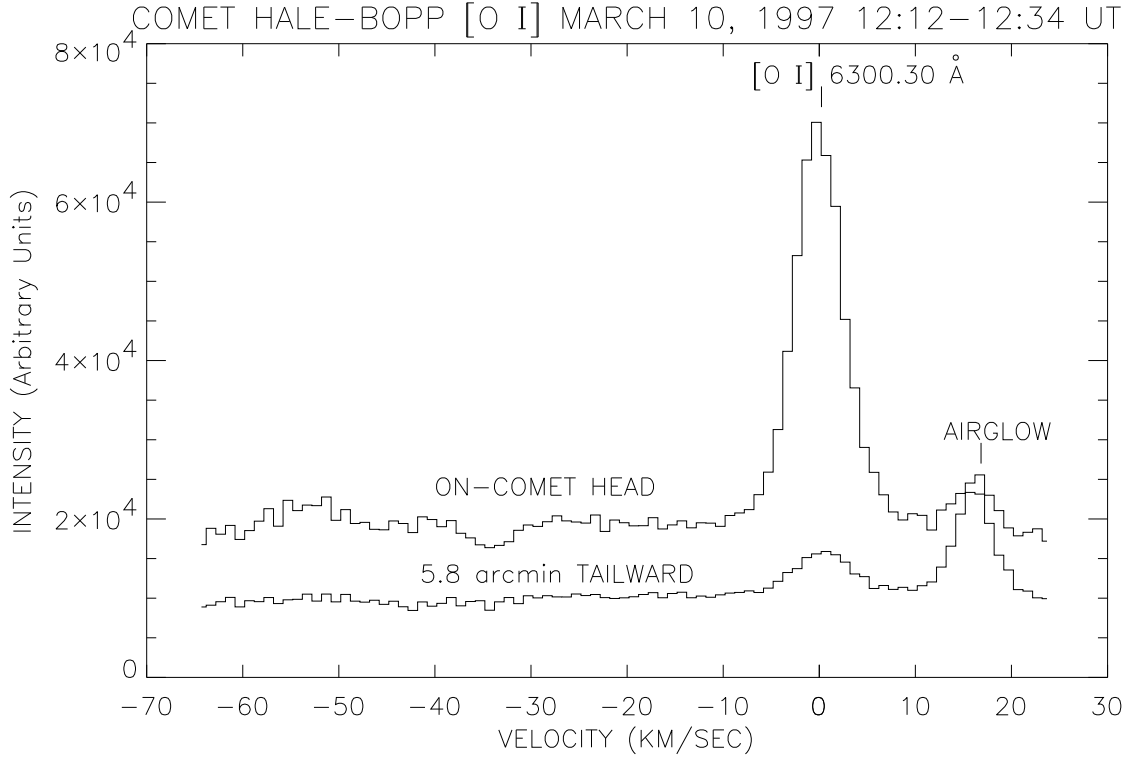


Figure 4: 2 inch Fabry-Perot spectrum of comet Hale-Bopp (March 10, 1997). Spectrum has ~ 4 km/s resolution.

Results

Figure 5 shows the average sky and continuum subtracted WHAM [O I] image. The WHAM image is overlayed with contours from a Monte Carlo Particle Trajectory Model (MCPTM) which predicts the [O I] emission in the coma of Hale-Bopp. As discussed in the introduction and seen from the model contours, the [O I] emission is expected to be spherically symmetric.

Figure 6 shows the radial profile measured by the WIYN hydra and densepack MOS together with radial profiles of the WHAM [O I] image. The WHAM data was divided into quadrants with the radial profile taken in each quadrant calculated

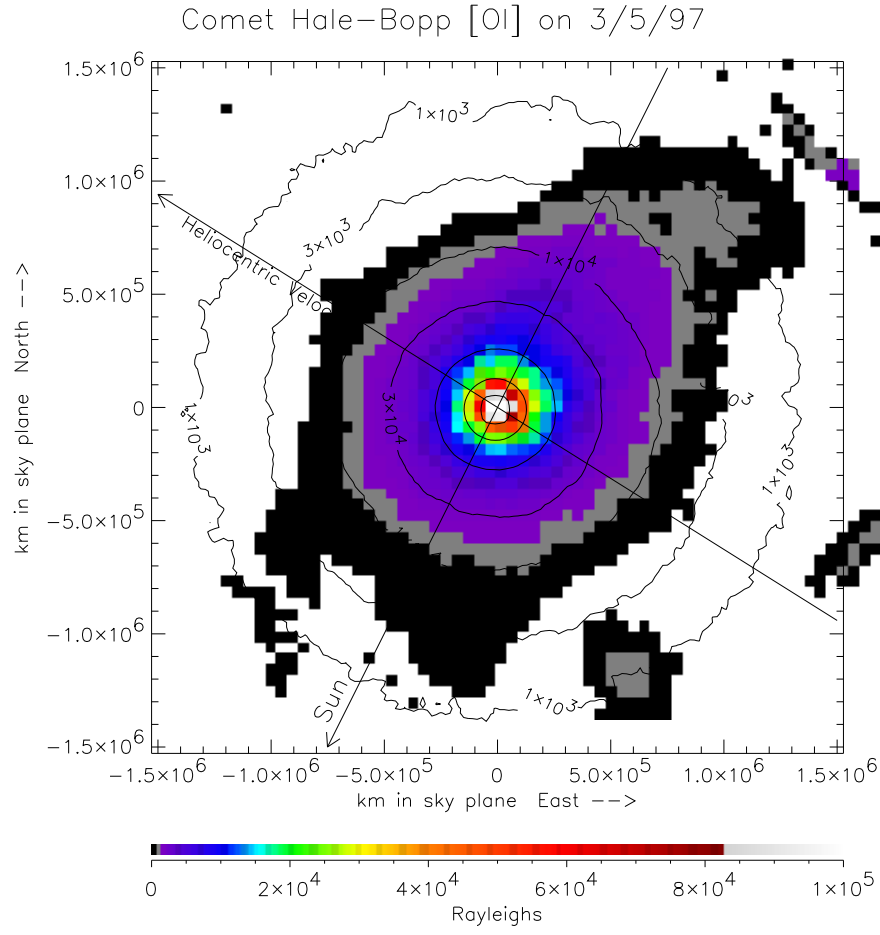


Figure 5: WHAM O(¹D) image overlaid with MCPTM model.

separately. Note the overall good fit of the MCPTM model to the data. The implied water production rates are 1.8×10^{31} molecules/sec for March 5 and 8.7×10^{30} molecules/sec for March 16.



Figure 6: Radial profile of $O(^1D)$ emission in comet Hale-Bopp normalized to an earth-comet distance of 1.427 AU (March 5, 1997).

Evidence for Tailward Asymmetry

The WHAM [O I] image shown in Figure 5 clearly shows extended emission in the direction of the dust tail. However, the flat-fielding of the WHAM image data is not well understood. Furthermore, the pass-band used to measure continuum emission is close to a cometary NH_2 line, which may confuse the continuum subtraction process. Thus, based on the WHAM image alone, we are cautious about claiming a detection of spatial asymmetry.

Evidence for Tailward Asymmetry (continued)

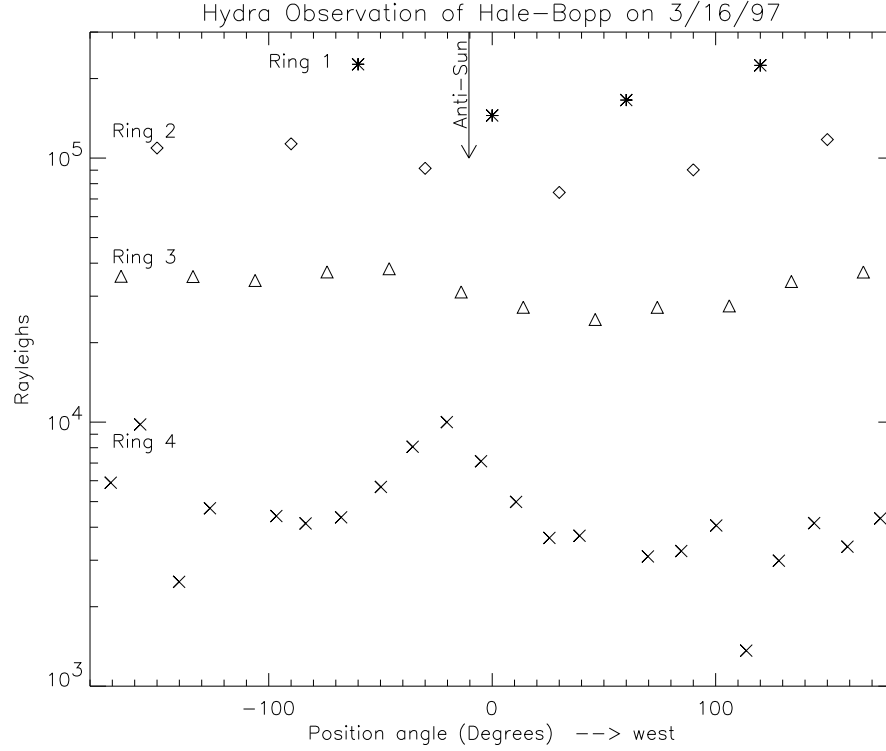


Figure 7: Polar plot of hydra $O(^1D)$ observations from March 16.

We also detect asymmetry in the $[O\ I]$ emission with the WIYN hydra instrument. Figure 7 shows the hydra data in a polar plot. The peak in “Ring 4” is consistent with the asymmetry seen in WHAM $[O\ I]$ distribution (Figure 5).

Conclusion

We have measured the $\text{O}({}^1\text{D})$ ($[\text{O I}]$ 6300 Å) emission in comet Hale-Bopp on March 5, March 16, and March 18. The Monte Carlo Particle Trajectory Model (MCPTM) of Combi & Smyth (1988, 1993) fits the data between 10,000 and 1×10^6 km, implying water production rates on these dates in the neighborhood of 1×10^{31} molecules/sec.

Observations on March 5, and March 16 with two independent instruments (one Fabry-Perot spectrometer operated in imaging mode, the other a multi-object spectrograph) both show excess emission in the tailward direction starting at projected distances from the nucleus of $\sim 250,000$ km. The source of this excess emission is currently not known.

References

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